REVIEW OF FENTON HILL HDR TEST RESULTS

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ABSTRACT

Results of recent flow testing at Fenton Hill, New Mexico, have been examined in light of their applicability to the development of commercial-scale hot dry rock (HDR) reservoirs at other sites. These test results, obtained during the cumulative 11 months of reservoir flow testing between 1992 and 1995, show that there was no significant production temperature drawdown during this time and that the reservoir flow became more dispersed as flow testing proceeded. Based on these test results together with previous HDR research at Fenton Hill and elsewhere, it is concluded that a three-well geometry, with one centrally located injection well and two production wells -- one at each end of the pressure-stimulated reservoir region -- would provide a much more productive system for future HDR development than the two-well system tested at Fenton Hill.

INTRODUCTION

The emphasis of this paper is on the major results of reservoir flow testing at Fenton Hill, NM from 1992 to 1995. A more extensive -- but non-inclusive -- summary of the results from 20 years of HDR research at Los Alamos National Laboratory’s Fenton Hill test site was presented at the World Geothermal Congress, 1995, in Florence, Italy (Brown, 1995). At the outset, it should be emphasized that in the original meaning, an HDR reservoir is a man-made geothermal system where the reservoir fluid is supplied by an engineered means, and geofluid production is managed so that under normal, steady-state operating conditions, the rates of injection and production are nearly the same, save for the amount of fluid lost from the periphery of the reservoir region. In this context, the surface fluid pressures and flow rates are under the control of the operator, whose main objective is to optimize the thermal power production from the reservoir under the constraint of an upper pressure limit above which the previously confined reservoir region will start to grow.

This paper emphasizes only three points that we feel are the most important results obtained from the 11-months of HDR reservoir flow testing conducted from 1992 to 1995. The first two points are based directly on the flow testing and related experimental data, while the third point, which draws on the total HDR experience at Fenton Hill and elsewhere, looks to the future of HDR. These points are as follows:

- There was no significant production temperature drawdown over 11 months of flow testing at Fenton Hill.
- The reservoir flow became more dispersed as flow testing proceeded.

- A three-well geometry (one injector and two producers) would provide a much more productive system for future HDR development than the two-well system tested at Fenton Hill.

NO SIGNIFICANT TEMPERATURE DRAWDOWN

Figure 1 presents a typical temperature profile across the openhole interval in the production well at Fenton Hill. This stepwise profile shows the principal joint intersections with the wellbore (at least 8 can be identified), while points A, B, and C represent fluid temperatures at selected depths along the production interval for comparative purposes. Point D represents the mixed-mean reservoir fluid production temperature at a location just above the highest flowing joint. The companion Table I lists the temperatures for these 4 points at 4 different times during the recent flow testing period.

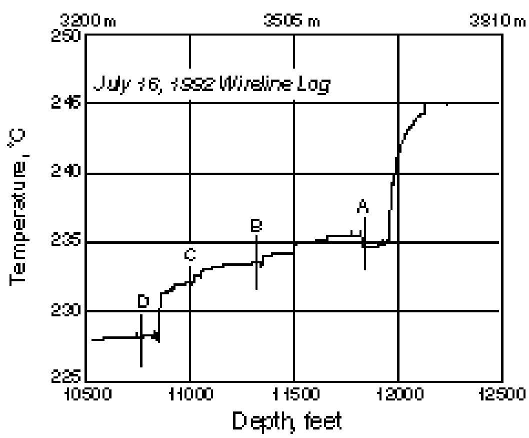

Figure 1. A typical temperature profile across the reservoir production interval.

Table I
Comparison of Fluid Temperatures at Four Specific PointsAcross the Production Interval, °C

Date of Log:	7/16/92	9/29/92	3/16/93	6/22/95
Point A, 3610 m (11,840 ft)	234.5	233.9	231.5	229.7
Point B, 3450 m (11,320 ft)	233.4	232.9	232.4	230.6
Point C, 3350 m (10,990 ft)	232.0	231.7	231.5	230.0
Point D, 3280 m (10,750 ft)	228.2	228.1	227.8	227.3

Two significant features of the reservoir thermal behavior can be discerned from the data shown in Table I. First, there was less than a 1°C cooldown in the reservoir outlet temperature (Point D) over the duration of flow testing between 1992 and 1995. Only 0.4° of this temperature drop occurred during the 8 months between July 1992 and May 1993, an interval representing the majority of the flow testing. However, there was a 0.5°C temperature drop during the much longer time interval between March 1993 and June 1995 which included a 2-year hiatus when the reservoir was shut-in, but maintained at a pressure level between 10 and 15 MPa.

Second, there appeared to be a flattening of the temperature profile across the production interval as the flow testing proceeded. This latter feature suggests that during both periods of pressure maintenance without flow, and during high-pressure flow testing with the mean reservoir pressure maintained at a level of about 24 MPa above hydrostatic, buoyant convection was active within the pressure-dilated joint network of the reservoir, tending to flatten the vertical temperature gradient at the production wellbore.

Without significant thermal drawdown (10 to 20°C at a minimum) accompanying an extended period of reservoir circulation, it is essentially impossible to determine the effective heat-transfer (i.e., circulating-flow-accessible) volume of an HDR reservoir. Even if the mean joint spacing were known, one could only obtain a lower bound to the size of the effective heat-transfer volume for the given circulation time. Figure 2 shows the modeled production temperature behavior for a fully flow-accessible HDR reservoir with a volume of 50 million m^3 and a flow rate of 31.5 l/s, for three effective joint spacings: 10, 25 and 50 m. These results were obtained using the GEOCRACK reservoir model developed at Kansas State University (McLarty, 1996).

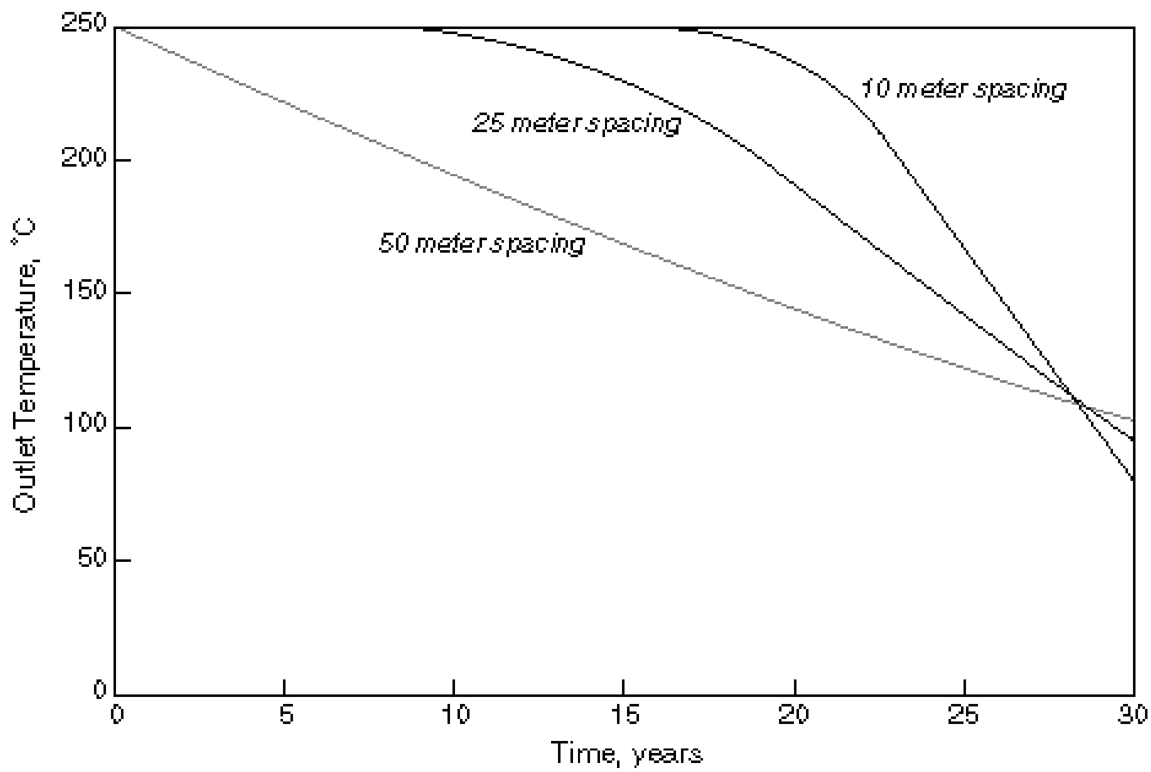

Figure 2. The influence of joint spacing on HDR reservoir production temperature profiles for a reservoir volume of 50 million m^3 per production well at a flow rate of 31.5 l/s. These results were obtained using the discrete element HDR reservoir simulator GEOCRACK (DuTeaux et al., 1996a, Swenson et al., 1995.

The predicted thermal drawdown results shown in Figure 2 should closely scale to the HDR reservoir at Fenton Hill, which had a circulating-flow-accessible (i.e., heat-transfer) volume of about 8 million m^3 (16% of the GEOCRACK modeled volume) and a production flow rate of 5.7 l/s (18% of the GEOCRACK modeled flow rate). Previously, a total fluid-accessible volume of 20 million m^3 had been determined for the Fenton Hill reservoir from a static (i.e., non-circulating) stepwise pressurization of the Fenton Hill reservoir from 7.5 to 15 MPa (Brown, 1991). The effective 8 million m^3 heat-transfer volume specified here was obtained by scaling down the reservoir region shown in Figure 3, to account for the large (roughly 60%), essentially unproductive, region south of the injection well.

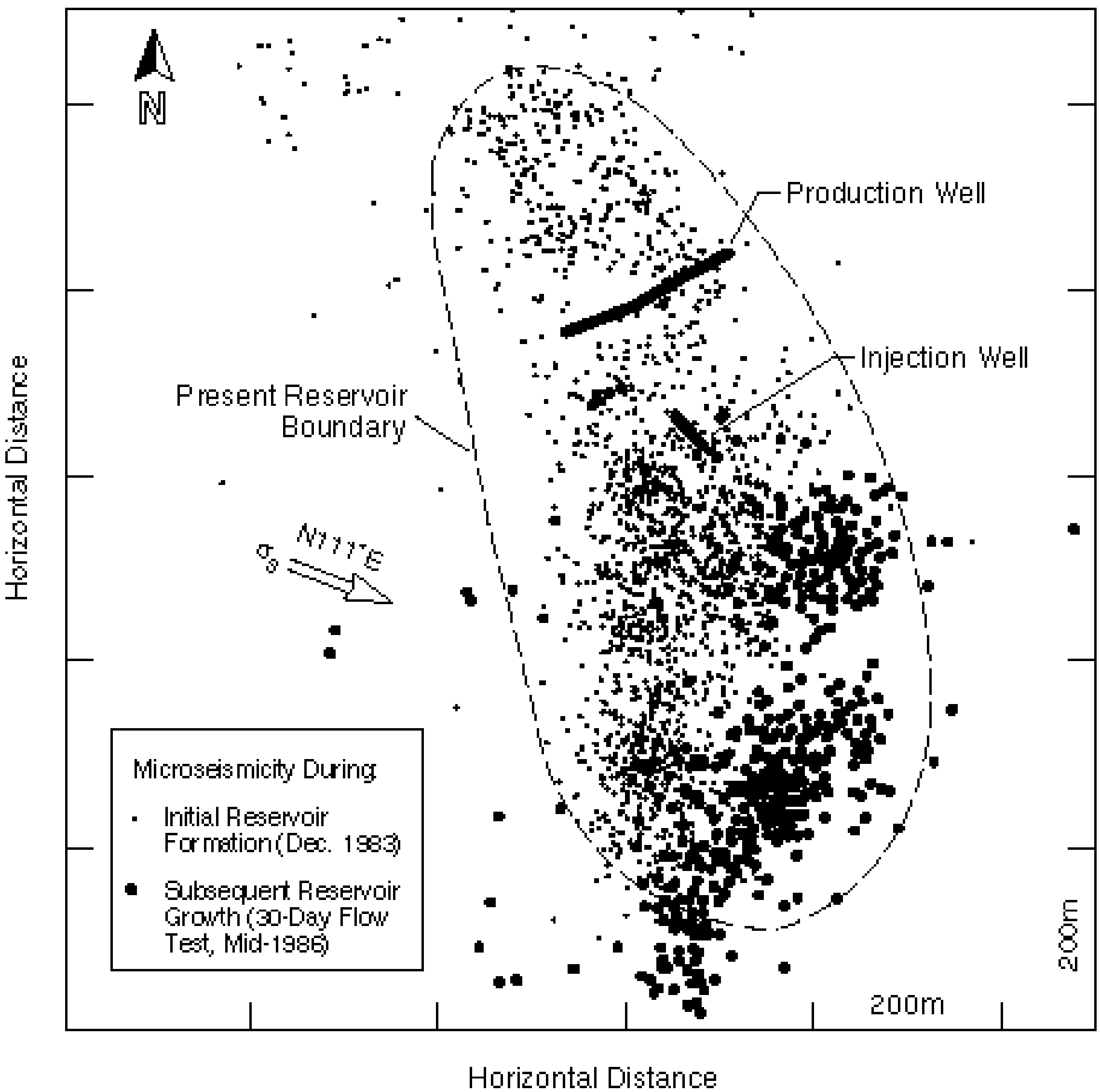

Figure 3: Plan view of the HDR reservoir at Fenton Hill showing the microseismic event locations for the two principal episodes of reservoir growth. The large region to the south of the injection well [encompassing most of the reservoir extension that occurred during the very high pressure initial 30-day flow test of the reservoir in 1986 (Dash, 1989)] is essentially a stagnant part of the reservoir that is unavailable for heat transfer to the fluid flowing mostly northward from the injection well to the production well.

Because of the asymmetrical, two-well configuration, the actual heat-transfer volume of the Fenton Hill reservoir is considerably less than the fluid-accessible volume that was determined from the non-circulating stepwise inflation of the reservoir. However, for future HDR reservoirs that are more fully accessed by employing two widely spaced production wells for each centrally located injection well, these two volumes should be essentially equivalent, since the majority of the stimulated reservoir region would then be accessible to the circulating fluid. In this latter case, the effective joint spacing within an HDR reservoir could be determined, after a minimum amount of cooldown, by applying a GEOCRACK discrete-element model similar to the one used to produce the curves shown in Figure 2.

THE RESERVOIR FLOW BECAME MORE DISPERSED WITH TIME

During the 11 months of flow testing between 1992 and 1995, the reservoir flow became more dispersed with time, rather than becoming more concentrated in a few flow paths as cooling proceeded. This is shown graphically in Figure 4 which depicts tracer responses on three occasions during this period of flow testing.

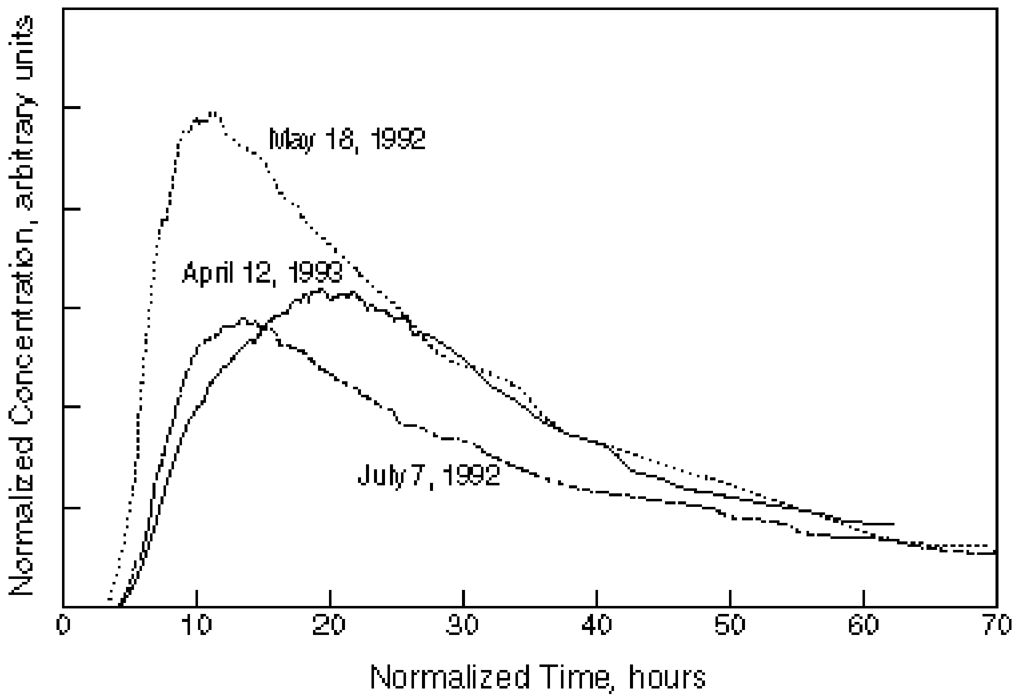

Figure 4. Recovery of fluorescein dye tracer on three occasions; early and late during the 8-months of flow testing in 1992-1993, and 4 weeks after renewed flow testing in 1995.

Although tentative at this time, it appears that when a large number of interconnected flow paths at various orientations are open during the high-pressure operation of an HDR reservoir, flow short-circuiting will not occur even after an extended period of circulation. However, as discussed by DuTeau and coworkers, there exists an upper limit to the circulating flow rate through an HDR reservoir, per unit volume of active reservoir, before the tendency to concentrate the flow in a few, more-direct flow paths develops (DuTeau et al., 1994).

The results shown in Figure 4 illustrate the great potential for tracers in interrogating HDR reservoirs at selected times during flow testing or during production from a commercial-scale reservoir. With a well-characterized conservative tracer, one could determine the temporal variation in the net aggregate of the reservoir flow paths and the effective (i.e., circulating) reservoir fluid volume, as was recently done at Fenton Hill. In addition, a conservative tracer run in conjunction with an appropriate adsorbing tracer could indicate the change in the effective reservoir heat transfer surface with time. A simulation of this type of result is shown in Figure 5, at the end of a continuous reservoir flow period of 10 years, using particle-tracking techniques built into the GEOCRACK reservoir model (DuTeaux et al., 1996b).

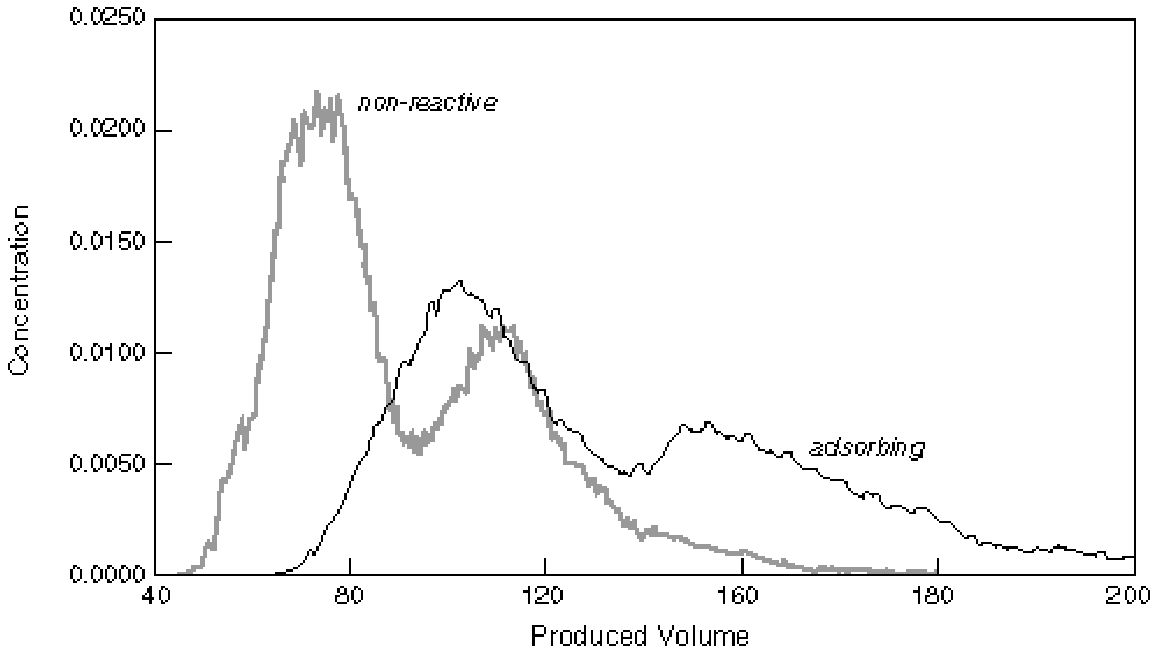

Figure 5. A comparison of non-reactive and adsorbing tracers at 10 years.

If one were able to adequately calibrate an adsorbing tracer in the laboratory or in a well-characterized in situ environment, the potential for determining the actual effective heat transfer surface in an HDR reservoir would exist. With a known effective reservoir heat-transfer volume as discussed above, it would then be possible to determine the mean joint spacing within the HDR reservoir -- and therefore its cooldown behavior and effective lifetime, as illustrated in Figure 2 above. These measurements could all be done during the early stages of production from the HDR system, when appropriate system or reservoir modifications could still be made to adjust the reservoir productivity and/or lifetime, if necessary.

ADVANTAGES OF A THREE-WELL HDR SYSTEM

From the Los Alamos experience at Fenton Hill during the development and testing of the present HDR reservoir, it is apparent that the pressure-stimulated reservoir region extended preferentially, but generally symmetrically, outwards from the injection well along an axis oriented approximately N 30° W -- S 30° E. This elongate, elliptically shaped region, as shown in Figure 3 above, developed in response to the preexisting joint patterns in the rock mass as influenced by the contemporary stress field.

Since the least principal earth stress (σ_3) at Fenton Hill is oriented N 111° E (Burns, 1991), it is apparent that the joint networks within the basement rock were more influential in determining the direction of reservoir development than the orientation of the least principal earth stress. Therefore, it is our view that the actual three-dimensional shape of an HDR reservoir will be principally influenced by the preexisting jointing patterns within the rock mass, as modified by the normally anisotropic in-situ stress field. The reservoir volume that actually develops can be characterized from the envelope of the microseismic events which occur during its formation and subsequent extension (Brown, 1990). After the reservoir is extended to its ultimate size, the actual levels of the in-situ stresses will play only a minor role in determining subsequent reservoir operating conditions.

Again referring to Figure 3 above, the basic problems inherent with any two-well HDR system are clear. First and foremost, if the reservoir region develops symmetrically around the injection well, then any one production well cannot possibly access the entire fractured reservoir. At best, only about half of the HDR reservoir will be accessible to flow from the centrally located injection well, if the reservoir develops in a roughly elliptical shape as occurred at Fenton Hill. Second, again as shown in Figure 3 above, any attempt to circulate at a very high injection pressure from the injection well to a single production well will undoubtedly result in unwanted reservoir growth on the side of the reservoir opposite from the production well, as occurred during the very-high-pressure flow testing at Fenton Hill in 1986 (Dash, 1989). Third, even if unwanted reservoir growth is prevented by reducing the injection pressure, the stagnant, high-pressure portion of the reservoir, besides being unproductive, will lead to greatly increased permeation water losses during operation.

The obvious solution to all three of these problems is to provide a second production well to access the dormant half of the reservoir region. This three-well configuration, at least for the example of Fenton Hill, would provide at least four times the thermal power output (Brown, 1994). This would be accomplished by operating at a significantly increased injection pressure level and flowing through twice the reservoir volume. At the same time, unwanted reservoir growth would be precluded by the pressure sinks provided by the production wells at either end of the reservoir, shielding those parts of the periphery most susceptible to extension from the higher injection pressures. In combination, the two production wells would tend to reduce the absolute rate of peripheral water loss for any given injection pressure since the average pressure level around the periphery of the reservoir would be reduced. Further, when calculated as a percentage of the production flow rate, the relative reservoir water loss would be very much reduced over the two-well system because of the greatly increased production flow provided by the three-well system.

SUMMARY

Recent flow testing results for the HDR reservoir at Fenton Hill have been examined for their applicability to the development of commercial-scale HDR reservoirs at other sites. These test results, obtained between 1992 and 1995, show that there was no significant drawdown in the geofluid production temperature during this time and that the reservoir flow became more dispersed as flow testing proceeded. Based on these test results, together with previous HDR research at Fenton Hill and elsewhere, it is concluded that a three-well system, with one centrally located injection well and two production wells at or near the farthest boundaries of the reservoir region, would provide a much more productive system for future HDR development than the two-well system tested at Fenton Hill.

Almost all the information of relevance to determining the actual optimum operating conditions for an HDR reservoir, including flow rate as a function of injection pressure, joint opening pressures as determined from gradual inflation and deflation pressure profiles, the fracture extension pressure, and overall flow impedance as a function of both the mean reservoir pressure and production backpressure levels, could be determined during the early phases of reservoir flow testing and subsequent reservoir extension, if necessary. Static (non-flowing) reservoir pressure testing could be employed to determine the flow-accessible heat-transfer volume as discussed above.

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